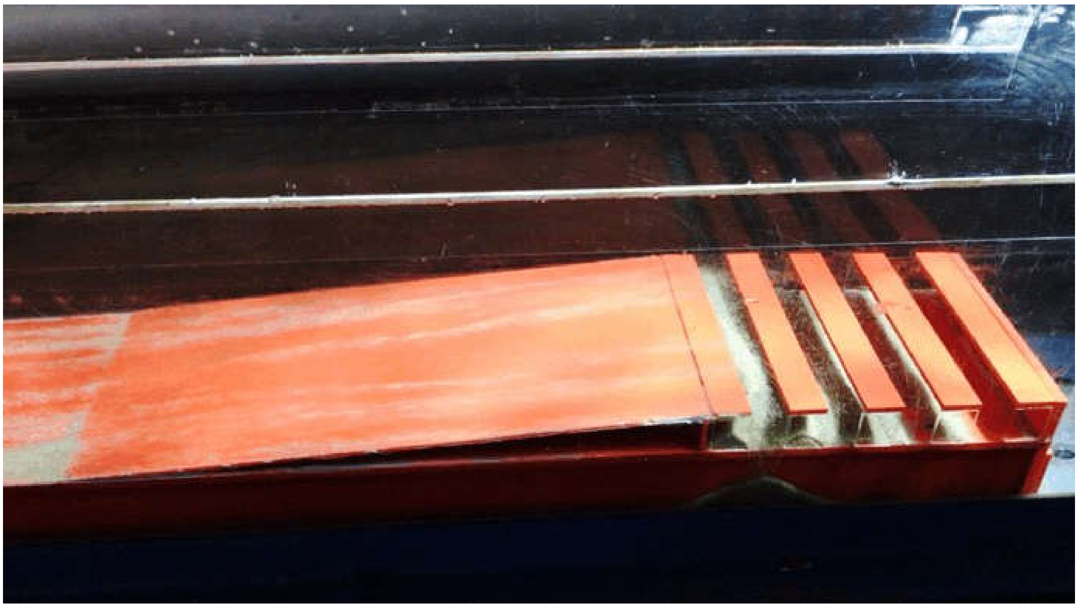
HydroCen Report nr.20

Flexible Sandtraps

Final Report

Kaspar Vereide, Wolfgang Richter, Ola Haugen Havrevoll, Kiflom Belete, Usha Shrestha, Ushanth Navaratnam, Gasper Mauko and Leif Lia



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Vereide K., Richter W., Havrevoll O. H., Belete K., Shrestha U., Navaratnam U., Mauko G. and Lia L. 2021. Flexible Sandtraps Final Report. HydroCen Report 20. Norwegian Research Centre for Hydropower Technology

Trondheim, January 2021.

ISSN: 2535-5392 (digital publication pdf)
ISBN: 978-82-93602-21-7

EDITOR
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COVER PHOTO
Ribs installed in the sandtrap model. Photo by Wolfgang Richter.

KEY WORDS
Hydropower, Upgrading, Flexibility, Sandtraps, Innovations.

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Abstract

Vereide K., Richter W., Havrevoll O. H., Belete K., Shrestha U., Navaratnam U., Mauko G., and Lia L. 2021. Flexible Sandtraps Final Report. HydroCen Report 20.

The Flexible Sandtraps (FlekS) project has been a four-year research project on upgrading of existing pressurized sandtraps in operational hydropower plants. Upgrading of existing sandtraps have several challenges compared with construction of new sandtraps; (i) limitations imposed by the existing infrastructure and (ii) the need to limit downtime to avoid production losses. The purpose of FlekS has thus been to develop cost-efficient solutions that can be installed with limited downtime to retrofit existing sandtraps in operational hydropower plants.

The project has been divided in three main activities; (A1) literature review and mapping of challenges in the hydropower industry, (A2) numerical simulations of preliminary concepts, and (A3) physical modelling of the most promising concepts. The literature review and mapping of challenges in the industry reveals that hydropower plants comprising over 8000 MW equaling about 25% of the total installed capacity in Norway have experienced challenges with silt, sand or gravel transported during operation. The challenges range from slightly faster than expected wear on the turbine to severe damages on the turbines and operational restrictions. Almost all these hydropower plants have existing pressurized sandtraps at the downstream end of the unlined headrace tunnel. Common for all is that a well-functioning sandtrap may be able to mitigate the challenges.

To find potential concepts for upgrading of existing sandtraps, numerical simulations and physical scale modelling have been applied. The sandtrap no. III at the 960 MW Tonstad hydropower plant has been used as a case study. Several field trips have been conducted and detailed information from the case-study has been made available, including a full 3D scan, velocity profile measurements from three ADCPs, pictures and videos taken during operation from a camera installed inside, and samples of the trapped material inside. The field data has been used to calibrate the numerical simulations and physical models. These tools have thereafter been used to test several different concepts for upgrading of existing sandtraps.

In conclusion, it is found possible to upgrade existing sandtraps with limited downtime and costs. The main conclusions from the FlekS research project are presented below.

1. Hydropower plants comprising over 25% of the total installed capacity in Norway have experience challenges related to transport of silt, sand and gravel during operation. Many existing sandtraps do not function satisfactory.
2. The FlekS-project confirms previous research that the closed type of sandtraps is superior compared with the open type of sandtrap for trapping of bed load. The main difference is that the closed type successfully separates the deposited material from the main water flow, preventing further transport as bed load or resuspension.
3. An efficient solution for upgrading of open sandtraps to closed sandtraps has been developed. The solution entails limited construction works in the downstream end of the sandtrap and does not require expanding of the sandtrap volume. This solution has been recommended for the upgrading of the case-study sandtrap at Tonstad power plant. Physical model tests at TU Graz indicate that this solution can increase the trap efficiency from 0% to 90% for particle sizes in the range 0.3 to 1 mm. Physical model tests at NTNU for particle sizes with d_{50} equal to 3 mm do not show any significant different in the trap efficiency for tests with and without ribs (about 87% for both situations).
4. The proposed solution includes the use of a flushing system, which is necessary to enable the minimum reconstruction works inside the sandtrap. Flushing systems are in general found to be a promising measure when upgrading existing sandtraps. Most of the Norwegian sandtraps reviewed in this work do not have a flushing system and require dewatering and manual removal of the deposited material. Flushing systems allow emptying of the deposited material without dewatering the sandtrap and will hence reduce both outage and the stress on the tunnel stability resulting from a dewatering.
5. The results concerning the effect of flow calming structures on the trap efficiency of sandtraps are inconclusive. Some tests show a positive effect, and some show a negative effect. A concept with a

passable flow calming structure was developed, allowing personnel and machines to pass the structure without dismantling during dewatering.

6. Heightening of the downstream weir was not found to have any effect on the trap efficiency. However, it can have a positive effect by preventing free surface flow with high velocities in the sandtrap.
7. Geometrical improvements are usually possible in existing sandtraps. Sudden expansions, contractions and abrupt changes in the geometry will cause turbulence and can decrease the trap efficiency of sandtraps.
8. For power plants where the sandtrap is constructed in conjunction with a surge tank, a new innovative solution for combined upgrading of the surge tank is developed. The “semi-air cushion surge tank” is able to increase the capacity of both the upper and lower surge chamber of two-chamber surge tanks with only expanding the volume of the lower chamber. Upgrading of the sandtrap may enable upgrading of the installed capacity in hydropower plants.
9. Physical model tests were not able to confirm any significant difference in trap efficiency for stable operation and transient operation of hydropower plants. However, only one test to investigate this effect was conducted and further research is necessary to conclude.

The results presented above are primarily based on the results from the physical scale models. However, it is experienced that numerical simulations and physical modelling and variations of the two methods gave significantly different results. Three different numerical simulation software were applied by different users and with different setup, and two different scaling methods for the physical modelling were applied. By comparing with the sand deposition in the field measurements, the results from the physical scale model from TU Graz seems to be most representative.

Developing scaling methods has not been an objective in the FlekS-project, and further research is necessary to investigate the accuracy of the two different scaling methods. Tests in the TU Graz model with the equivalent same sand size as applied in the NTNU model are planned to check if the difference in results is still significant. Tests are also planned to be conducted according to the Euler scaling method with lightweight material (natural sand is not possible at scale 1:37 owing to cohesion). Also, field data from the future case-study Tonstad sandtrap with installation of the ramp and a short section with ribs, will provide more information to validate the physical scale models. Further investigation of the numerical simulations methods is also required. The turbulence models and necessary resolution, in addition to the particle simulation and two-way coupling between water and particles needs further testing to give credibility as a design method for pressurized sandtraps.

A PhD project in HydroCen will continue parts of the work described in this report. The physical models, the field data, and the 3D geometry are still available for future research, teaching and master thesis work.

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Foreword

Sandtraps are an essential part of the Norwegian hydropower concept. The sandtrap enables unlined tunneling and reduce costs and time before the power plant is commissioned. However, the design of sandtraps is challenging as the physical behavior is complex two-phase flow with particles and water. Even though the early development of design concepts were done with physical scale modelling, the main driver has been testing in full scale in operation power plants where, sadly, many designs were unsuccessful. Still today, many of these suboptimal sandtraps are in operation, and there is a potential for improvement.

New methods with both numerical and physical modelling enables new potential for design of sandtraps. In the FlekS project we wanted to utilize the new opportunities to further improve the otherwise impressive Norwegian hydropower plants.

Personally, I believe the sandtrap will also be a part of the future generation hydropower plants. Many Norwegian hydropower plants have brook intakes and long unlined tunnels with rock material remaining after the construction. Thus, when constructing a pressurized sandtrap in the downstream end of the unlined tunnels, it is an all-in-one solution.

FlekS has been an enjoyable project with many unexpected findings. We have solved the objectives and have proposed a solution to improve the existing sandtrap at the 960 MW Tonstad hydropower plant. However, we also see much potential for further research. We see potential for further improvement of both the design methods and the design of pressurized sandtraps.

Trondheim, January 2021
Kaspar Vereide
Project Leader

1 Introduction

This chapter presents the background and scope of the project, the methodology and the applied case-study, and finally the organization and financing of the project.

1.1. Background

The Flexible Sandtraps (FlekS) project has been motivated by the need to allow increased flexibility from existing hydropower plants. During the project period, the 1400 MW NordLink cable between Tonstad in Norway and Wilster in Germany was under construction and became commissioned in December 2020. This cable, in addition to increased construction of wind power in Norway and its neighboring countries are expected to increase the value of flexibility. As a part of the FlekS-project, it was found that hydropower plant comprising over 25% of the total installed capacity in Norway have experienced challenges related to the sandtraps. These challenges result in operation restrictions and limits the flexibility in several of these power plants.

The FlekS project was initiated by Sira-Kvina kraftselskap in February 2017. The motivation in the company was to solve long-term operational challenges concerning transport of sand and gravel in the tunnel system of the 960 MW Tonstad hydropower plant. The challenges include events where large amounts of sand and gravel had been flushed from the pressurized sandtraps and down into the turbines causing damage. In addition, owing to a more flexible operation of the power plant an increased amount of sand and gravel was being transported to the sandtraps in recent years, increasing the risk of turbine damage. To avoid flushing the sandtraps, operational restrictions have been enforced on the power plant operation, reducing the flexibility of operation and hence the economic profit.

There exist numerous previous studies of sandtrap design. However, no previous literature was found on upgrading of existing pressurized sandtraps. Upgrading of existing sandtraps have several challenges compared with construction of new sandtraps:

- Limitations imposed by the existing infrastructure.
- The need to limit downtime to avoid production losses.

The purpose of FlekS has thus been to develop cost-efficient solutions that can be installed with limited downtime to retrofit existing pressurized sandtraps in operational hydropower plants.

1.2. Scope of Work

The FlekS project has been a four-year research project. The main research objective has been to: *Develop solutions for upgrading of existing sandtraps in hydropower plants.* Secondary objectives have been to:

- Review of existing literature on sandtraps, map related challenges in the industry and gather field data.
- Investigate possible solutions for upgrading of existing sandtraps with numerical simulation tools.
- Investigate possible solutions for upgrading of existing sandtraps with physical scale modelling.

As a part of this work, it has been the target to propose a specific solution to implement in the sandtrap III in Tonstad hydropower plant, to solve the challenges related to transport of sand and gravel through the turbines.

1.3. Organization and funding

The FlekS project has been organized according to Figure 1. The research partners have been involved in the definition of the scope-of-work, and methodology in addition to the actual research. The project has been an associated project to the ongoing FME HydroCen.

The project has been divided in three main activities: (A1) literature review, (A2) numerical simulations, (A3) physical scale modelling. Researchers from both NTNU and TU Graz have been involved in all the three activities.

To ensure coordination between the different activities, regular meetings with scientific discussions has been organized. The work has also been presented at HydroCen events and workshops where feedback from the user partners has been received. Four field trips into the sandtrap no. III of Tonstad hydropower plant has been conducted.

The project has been funded by the Regionalt forskningsfond for Agder (RFFA). The purpose of RFFA is to initiate and support regional industrial research projects. The total budget of FlekS has been approximately 5.0 mill. NOK over a four-year period. The funding was split in 3.0 mill. NOK to NTNU, 1.0 mill. NOK to TU Graz and 1.0 mill. NOK to Sira-Kvina. The budget at Sira-Kvina includes common expenses, administration, and project management.

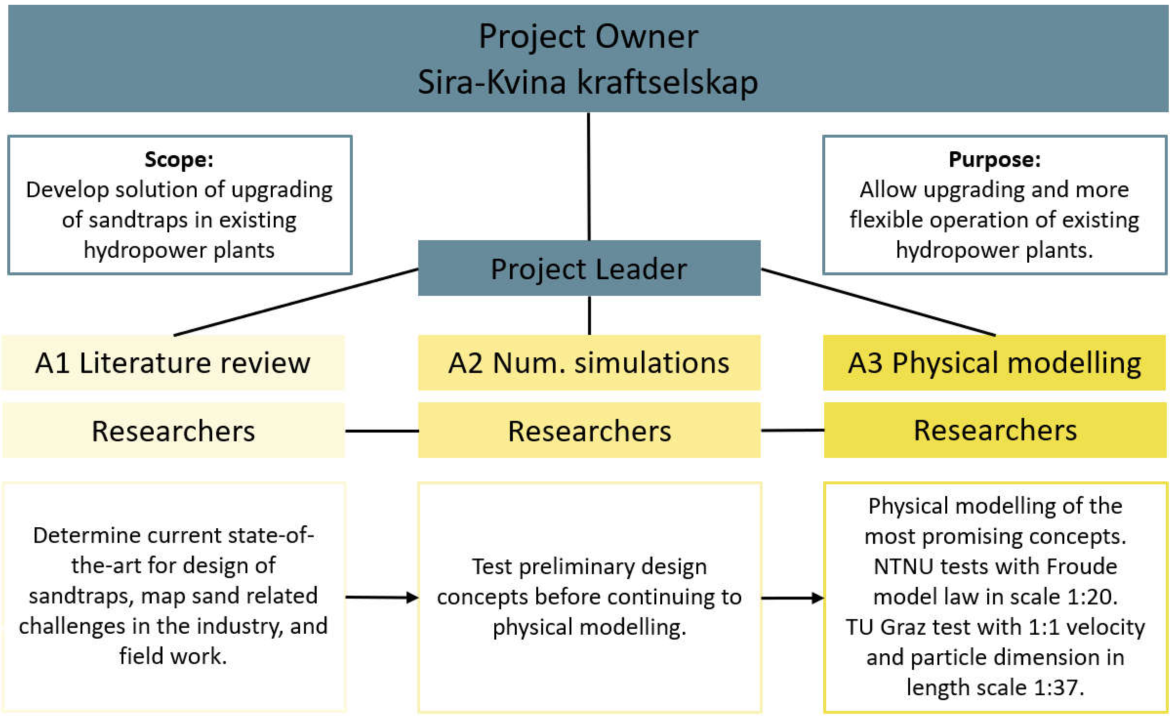

Figure 1: Organization of the FlekS project.

Several adjustments of the project were done during the project period. Originally, the project scope included implementation and testing of a concept in full-scale at Tonstad hydropower plant. However, as a part of the work, it was found that more testing and development in the laboratory was necessary. The budget was hence redistributed to increase the laboratory efforts. Full-scale testing is now planned in 2023, when the sandtrap III in Tonstad power plant will be taken out of operation for 6 months owing to upgrade of the control systems of the power plant.

The FlekS-project was originally intended to be completed in 2019. However, owing to complications during construction of the physical model at NTNU, the project deadline was postponed. The global Covid-19 pandemic further delayed the project, which was finally completed in December 2020.

2 Methodology

The work has been conducted through a case-study of the sandtrap no. III in the 960 MW Tonstad hydropower plant. Four field trips to the sandtrap were conducted together with the hydropower plant owner and operator Sira-Kvina kraftselskap. In addition, 3D scanning, results from previous field measurements, drawing and design reports for the sandtrap was made available for the FlekS project. The project has been divided in three main activities: (A1) literature review, mapping of challenges in the hydropower industry, and field work, (A2) numerical simulations of preliminary concepts, and (A3) physical scale modelling of the most promising design concepts. Furthermore, several master theses were conducted as a part of the project that allowed more detailed investigation on several aspects. This allowed for combination of education and widening the range of investigations in the project. The methodology for each activity is presented and discussed below.

2.1. Activity A1: Literature review, mapping of challenges in the hydropower industry, and field work

A literature review was conducted to map the historical and current state-of-the art for design of pressurized sandtraps. The reviewed material includes recognized scientific journals within the field of hydraulic engineering, textbooks, and reports. It was chosen to focus specifically on pressurized sandtraps for hydropower plants, excluding general particle and particle handling literature. It was also chosen to make a distinction between pressurized sandtraps constructed to trap bed load, and desilting basins made to stop suspended load.

In addition to the literature review, a mapping of challenges related to sand transport in Norwegian hydropower plants has been conducted. The mapping is based on available literature and direct communication with personnel at some of the major hydropower companies in Norway. A list of hydropower plants currently experiencing such challenges is provided. Finally, results from field work and the available data on the case-study pressurized sandtrap at the 960 MW Tonstad hydropower plant is presented. Table 1 presents the researchers working in activity A1.

Table 1: Researchers working in activity A1

Name	Title	Task
Ola Haugen Havrevoll (NTNU)	PhD candidate	Literature review, mapping of challenges in the hydropower industry, field work
Kaspar Vereide (Sira-Kvina/NTNU)	Adj. Ass. Prof.	Literature review, mapping of challenges in the hydropower industry, field work
Wolfgang Richter (TU Graz)	Researcher (PhD)	Literature review
Sofie Marie Steinkjer (NTNU)	Master student	Field work
Mads Ivarson (NTNU)	Master student	Field work

2.2. Activity A2: Numerical simulations of preliminary concepts

Three-dimensional (3D) computational fluid dynamics (CFD) numerical simulations were applied to test preliminary concepts for upgrading of sandtraps in existing hydropower plants. The benefit of 3D CFD compared with physical model tests is the ability to adapt the computational accuracy according to the design phase, allowing to run multiple simulations fast in the early phase, and progressing into more accurate and detailed simulations for a few selected cases in the detailed design phase. 3D CFD also allows for simulation in both model scale and prototype scale, avoiding the challenges related to scaling effects in physical model tests. However, 3D CFD requires compromising on the turbulence detailing compared with the prototype and a physical model test.

3D CFD has been performed primarily at TU Graz with supplementary simulation by MSc students from both TU Graz and NTNU. Three students have completed their thesis, and two are currently ongoing. Table 2 presents the researchers working in activity A2, including the 3D CFD software they have applied. CFD simulations have been conducted with several different approaches including:

- One-phase flow to study the flow conditions
- Two-phase flow with particle concentration methods (with and without coupling)
- Two-phase flow with discrete particle modelling (with and without coupling)

The different CFD software provide different tools and packages that have different advantages and disadvantages. In this project, a wide range of tools and approaches have been utilized, providing a sound basis to draw general conclusions.

Table 2: Researchers working in activity A2

Name	Title	Task	Software
Wolfgang Richter (TU Graz)	Researcher (PhD)	Hydraulic design, CFD simulations	Ansys CFX
Kaspar Vereide (Sira-Kvina/NTNU)	Adj. Ass. Prof.	Hydraulic design	-
Ola Haugen Havrevoll (NTNU)	PhD candidate	Hydraulic design	-
Kristian Sagmo	Post Doc.	Hydraulic design, CFD simulations	Siemens StarCCM++
Rakel Næss (NTNU)	Master student	CFD simulations	Ansys Fluent
Mads Ivarsson (NTNU)	Master student	CFD simulations	Ansys CFX
Lars Torgeirsson Lauvsletten (NTNU)	Master student	CFD simulations	Ansys Fluent
Lukas Sterner (TU Graz)	Master student	CFD simulations	Ansys CFX

2.3. Activity A3: Physical scale modelling of the most promising concepts

Physical scale modelling was applied to test the most promising concepts for upgrading of sandtraps in existing hydropower plants. The main advantage of physical modelling compared with CFD are reduced amount of possible error sources and accuracy of turbulence and sand-water interaction. In a physical model, the water, sand and gravity are real, and the turbulence and sand-water interaction are fully resolved. However, the scaling method and scaling factor is of crucial importance. The disadvantages of physical modelling are the construction time, costs, and the scaling effects. Scaling effects are especially challenging for models with two phase flow, such as in this case with water and particles, where the two phases are influenced differently by the scaling. To mitigate and control for scaling effects, two models were constructed, one at NTNU in scale 1:20 and one at TU Graz in scale 1:37. In combination with 3D CFD the approach has been hybrid modelling, where the different benefits of the different methods has been utilized and combined.

The two physical models have utilized different scaling laws. At NTNU, the model is scaled according to the Euler scaling law, where the relation between the inertia forces and pressure forces are preserved. At TU Graz, only the geometry is scaled, while the water velocity and particle diameter are preserved equal as in the prototype. The scaling method applied at NTNU has been utilized in previous studies presented by Mattimoe et al. (1964), Johansen (1967) and Svee (1973). The scaling method applied at TU Graz has been applied by Mattimoe et al. (1964), Jong et al. (1992) and Develay et al. (1999). The scaling method applied at TU Graz was also investigated and validated by 3D CFD simulation. There was not found previous literature with documentation on which of the two methods is superior.

Natural sand has been chosen as the injected material at both NTNU and TU Graz. Experiments with different material including natural sand, carbonate rock and lightweight PMMA was tested and evaluated for further use by the master student Steinkjer (2018) and Daxnerová (2019). Both natural sand and lightweight PMMA was recommended for further use, but owing to availability and costs, it was chosen to proceed only with natural sand at both NTNU and TU Graz.

Seven researchers have been involved in the physical model experiments at NTNU, and two researchers have been involved in the experiments at TU Graz. Three master students have completed their master thesis as a part of the work on physical modelling in the FlekS project. Table 3 presents the researchers working in activity A3, including the tasks they have worked on.

Table 3: Researchers working in activity A3

Name	Title	Task
Kiflom Belete (NTNU)	Researcher (PhD)	Project leader NTNU model
Usha Shrestha (NTNU)	Researcher (MSc)	Conducting experiments
Kaspar Vereide (NTNU)	Adj. Ass. Prof.	Test plan and model design
Ola Haugen Havrevoll (NTNU)	PhD candidate	Project leader PIV tests
Ushanth Navaratnam (NTNU)	Post Doc.	Conducting PIV tests
Leif Lia (NTNU)	Prof.	Test plan and model design PIV-tests
Wolfgang Richter (TU Graz)	Researcher (PhD)	Project leader TU Graz model Conducting experiments
Gasper Mauko (TU Graz)	Master student	Conducting experiments
Jana Daxnerova (NTNU)	Master student	Conducting experiments
Sofie Marie Steinkjer (NTNU)	Master student	Conducting experiments

3 Literature review, mapping of challenges in the industry, and field work (A1)

This chapter presents results from activity A1. The literature review included articles from recognized scientific journals within the field of hydraulic engineering, textbooks, and reports. It was chosen to focus specifically on pressurized sandtraps for hydropower plants, excluding general particle transport and particle handling literature. It was also chosen to make a distinction between pressurized sandtraps constructed to trap bed load, and desilting basins made to stop suspended load. An overview of the reviewed material is presented in the Table 4. In addition to the literature review, a mapping of challenges related to sand transport in Norwegian hydropower plants has been conducted. A list of hydropower plants currently experiencing such challenges is provided. Finally, results from field work and the available data on the case-study pressurized sandtrap at the 960 MW Tonstad hydropower plant is presented.

3.1. Literature review

The literature review reveals that design of pressurized sandtraps has been an ongoing subject with many different design concepts and research methodologies. A peer review publication with a state-of-the-art-review is currently in process and will contain detailed description of the historical development of sandtrap design. An overview of the reviewed material is presented in Table 4 and a summary is given in the following.

The early versions of sandtraps constructed in the 1960's where very short and constructed as a sudden expansion immediately upstream the pressure shaft. These sandtraps could effectively stop larger rocks and boulders, but were ineffective against gravel, sand and silt. This design is found in the 60 MW Tussa hydropower plant commissioned in 1961, where the operator currently experiences challenges related to transport of gravel through the turbines.

The second generation of sandtraps in Norway were the long and open sandtraps constructed as a longer section of the tunnel with a larger cross-section. The concept was to reduce the flow velocity sufficiently to allow the particles to settle and get trapped. This concept is regarded as the most typical design in existing Norwegian hydropower plants. This design is found in the 960 MW Tonstad hydropower plants commissioned in 1968, where the operator currently experiences challenges related to transport of sand through the turbines.

The third generation sandtraps where the closed type, where the bottom part of the sandtrap was separated from the main flow with horizontal ribs as shown by Eggen (1973) and VR (1984). An interesting observation is that this is the same concept developed and tested at the Jaybird power plant (Mattimoe et al. 1964). This design is also currently regarded as the state-of-the-art. This design is found in the 120 MW Tjørhom hydropower plant commissioned in 1973, where the operator does not experience challenges related to transport of particles through the turbines.

There has not been found previous literature on upgrading of existing sandtraps. This has been suggested as a measure for hydropower plants with poorly performing sandtraps in the past, but investigation on the optimum concepts for such upgrading is missing. The FlekS project will hence fill the missing gap of knowledge.

3.2. Challenges related to sand transport in the Norwegian hydropower industry

To assess the magnitude of sand related challenges in the Norwegian hydropower industry, a mapping has been conducted as a part of FlekS. The mapping is based on available literature and direct communication with personnel at some of the major hydropower companies in Norway, Statkraft, Hydro, Sira-Kvina, E-CO, Trønder Energi and BKK. Table 5 presents the results from the mapping. The list is not complete but demonstrates that sand related challenges is a significant issue. The total installed capacity of these power plants is almost 8000 MW, amounting to over 25% of the total installed capacity in Norway.

Table 4: Sources of information

Type	Sources	Most important references
Scientific journals	ASCE Journal of Hydraulic Engineering ASCE Journal of Hydraulic Research ASCE Journal of the Hydraulic Division Journal of the Power Division International Journal of Hydropower and Dams	- Rock trap experience in unlined tunnels (Mattimoe et al., 1964) - Movement of sand in tunnel (Lysne, 1969). - The design of unlined hydropower tunnels and shafts: 100 years of Norwegian Experience (Broch and Palmström, 2017). - Design and functional requirements for rock traps for hydropower pressure tunnels (Brox, 2016). - Studies of particle sedimentation basin design (Camp, 1959). - Three-dimensional numerical modeling of water and particle flow in a sand trap (Olsen and Skoglund, 1994). - Three-dimensional numerical modelling of bed changes in a sand trap (Olsen and Kjellesvig, 1999). - Desilting basin system of the Dul Hasti Hydroelectric Project (Develay et al., 1999). - Multiple solutions of the Navier-Stokes equations computing water flow in sand traps (Almeland et al. 2019).
Conference papers	Various.	- Hydraulic Model Studies of Desilting Basins of a Hydro-electric Project (de Jong et al., 1992). - A scouring rock trap in Lemonthyne power tunnel (Griffiths and Brett, 1974). - Split and settle – a new concept for underground desanders (Støle, 1997).
Textbooks	Various.	- Wasserkraftanlagen (Giesecke et al. 2014). - Hydraulic Design (Lysne et al. 2003). - Physical models and laboratory techniques in coastal engineering (Hughes, 1993). - Hydraulic Modelling (Kobus, 1980)
Reports	Electric Power Research Institute (EPRI) Norsk Hydroteknisk Laboratorium (NHL) Energibedriftenes landsforening (EBL) Vassdragsregulantenes forening (VR)	- Design guidelines for pressure tunnel and shafts (Ripley and Brekke, 1987). - Sandtransport og sandfang i kraftverktuneller (Eggen, 1973). - Sandtransport i tuneller – laboratorieundersøkelser (Lysne, 1968). - Modellforsøk av silosandfang (Solvik, 1975). - Sandslitasje på vannkraftturbiner (VR, 1984). - Ulla-Førre verkene, tunnelrensk, sandfang (Dahl and Tvinnereim, 1975). - Tjørhom kraftverk, sandfang fordelingsbasseng, modellforsøk (Svee, 1973). - Tonstad kraftverk, sandfang- og strømningsundersøkelser (Johansen, 1967). - Blåfalli ii kraftstasjon – sandfang. (Tvinnereim, 1971)
PhD theses	Norwegian University of Science and Technology (NTNU) Ecole Polytechnique federale de Lausanne (EPFL) Eidgenössische Technische Hochschule Zürich (ETH)	- Entsander von wasserkraftanlagen (Ortmanns, 2006) - Design optimization of desanding facilities for hydropower schemes (Paschmann, 2018). - Experimental investigations on suspended, hydro-abrasive erosion and efficiency reduction of coated pelton turbines (Felix, 2017).

Table 5: Power plants with sand problems

Power plant	Capacity [MW]	Reported severity	Problem description
Kvilldal	1240	Low	Minor wear on the turbines.
Sima	1120	High	Wear on the turbines and frequent maintenance.
Tonstad	960	High	Wear on turbines. Danger of flushing sandtrap and larger particles during mass oscillation downsurge and filling of the sandtrap resulting in operational restrictions.
Svartisen	600	Medium	Wear on the turbines.
Rana	500	Medium	Wear on the turbines.
Tokke	430	Medium	Wear on the turbines.
Lio	335	High	Wear on the turbines and frequent maintenance.
Evanger	330	High	Wear on the turbines and frequent maintenance.
Kobbelv	300	Medium	Wear on the turbines.
Aura	290	Medium	Wear on the turbines.
Jostedal	290	Medium	Wear on the turbines.
Skagen	270	High	Wear on the turbines and frequent maintenance.
Mauranger	250	Medium	Wear on the turbines and frequent maintenance.
Tysso II	220	High	Wear on the turbines and frequent maintenance.
Duge	200	High	Clogging of seals in the main inlet valve resulting in operational restrictions.
Driva	140	Low	Wear on the turbines.
Leirdøla	125	Medium	Wear on the turbines.
Olden	112	Medium	Wear on the turbines.
Aurland II L	63	Medium	Wear on the turbines.
Tussa	60	High	Wear on the turbines and frequent maintenance. Operational restrictions.
Bjerka	20	High	Wear on the turbines and frequent maintenance.

Detailed data describing the sources of particles, the damages they inflict and resulting costs, and possible measures are presented in the report "Sandslittasje på vannkraftturbiner" by Vassdragsregulantenes Forening (1984). Field data and evaluation of problems at more than 15 hydropower plants are provided in this report. The field data demonstrates that the most typical source is from intakes and secondary intakes (brook intakes) disproving a common belief that the main source is from the unlined tunnel. For newly commissioned power plants with unlined tunneling and remaining material on the invert, this material will normally contribute to a significant amount of particle transport in the first years of operation. However, long-term problems are usually caused by continuous inflow of particles to the intakes.

The reports describe several possible measures to reduce the challenges, including construction of sandtraps directly at the inlet, pressurized sandtraps in the tunnel system, and turbine design and reinforcement. For power plants with particles originating from a single intake, a sandtrap at this location is often recommended. However, for power plants with numerous intakes or an unknown particle source it is more rational to construct a pressurized sandtrap at the downstream end of the tunnel. A well-functioning pressurized sandtrap will stop particles independent of the source.

However, operational experience from several hydropower plants have shown that many sandtraps do not function satisfactory. In addition, previously functional sandtraps may also become dysfunctional after upgrading of the installed capacity in existing hydropower plants, such as in the 220 MW Tysso II and the 270 MW Skagen power plants.

The mapping of sand related problems in the Norwegian hydropower industry proves that there is potential for improvement. New concepts for cost-efficient upgrading of existing sandtraps may thus receive widespread application.

3.3. Field work and field data from the case-study

This section presents field work conducted as a part of FlekS, and available field data from previous projects. Four field trips to the sandtrap were conducted together with the hydropower plant owner and operator Sira-Kvina kraftselskap. In addition, 3D scanning, results from previous field measurements, drawing and design reports for the sandtrap was made available for the FlekS project.

Figure 2 presents a schematic drawing of Tonstad hydropower plant. The tunnel system is complex with two upper reservoirs hydraulically connected, eight brook intakes, three pressure shafts with separate surge tanks and sandtraps. Pressure shaft no. I and no. II each has two 160 MW turbines, while pressure shaft no. III has one 320 MW turbine.

Sandtrap no. III has been the case-study for the FlekS-project. This sandtrap protects the second largest hydropower unit in Norway and is vital to successful operation of this power plant. However, since its commissioning, several incidents with transport of large amounts of sand and gravel into the turbine has encountered. The power plant currently operates with operational restriction to prevent such incidents. One motivation of the FlekS-project is hence to be able to improve the current situation.

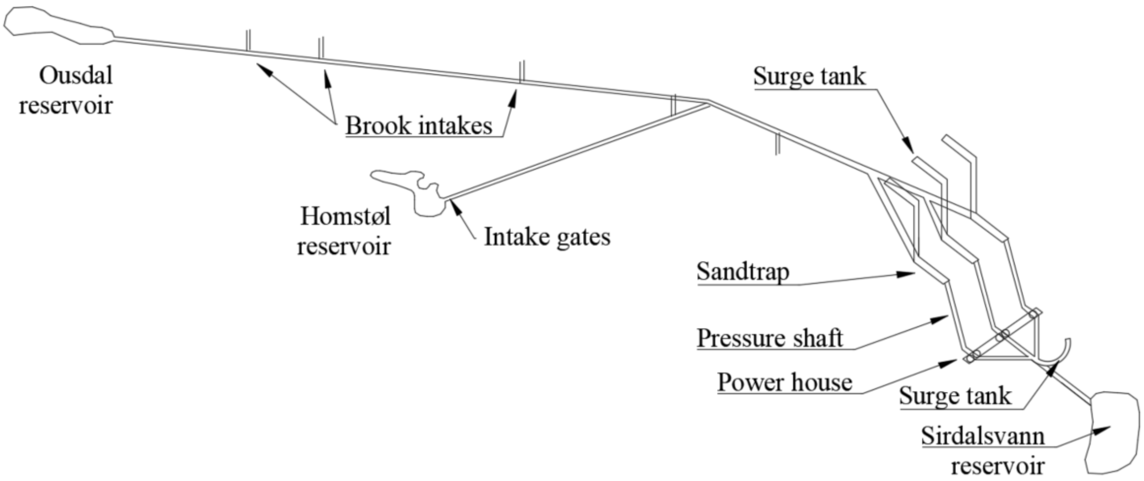

Figure 2: Schematic drawing of the 960 MW Tonstad hydropower plant

Previous studies have been conducted with sandtrap no. III as case-study. A full 3D scanning of the entire sandtrap and ADCP measurement of the horizontal velocity profile in three locations was conducted as a part of the PhD work of Bråtveit (2015). These data have been made available for the FlekS-project. Figure 3 presents a 3D model of the sandtrap and surge tanks, indicating the flow direction and the position of the pressurized sandtrap no. III. The sandtrap is about 200 m long and has a cross sectional area of about 110 m^2. The design flow is 80 m^3/s resulting in an average flow velocity of about 0.7 m/s in the sandtrap. There is a gate with dimensions 4x7 m in the upstream end, and a trashrack at the transition to the pressure shaft in the downstream end. In between is an access tunnel leading to a gated plug, used for access during inspections and manual removal of the deposited material. The sand trap is normally dewatered and cleaned every 2 years.

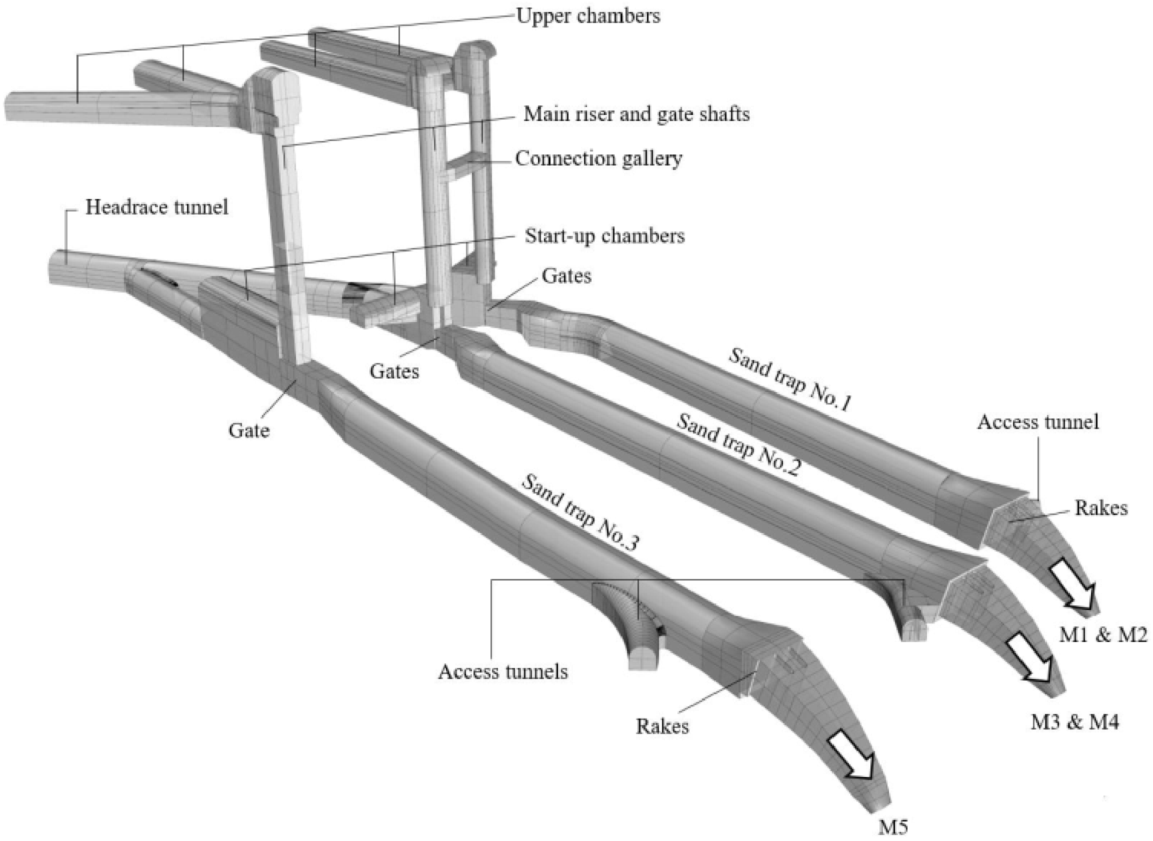

Figure 3: Three-dimensional (3D) model of the Tonstad surge tanks and sandtraps

Four field trips to the site have been conducted as a part of the FlekS project. As a part of the field work, the particle deposition has been mapped and samples of the deposited material has been collected. Figure 4 present a photo of the sand deposition in front of the weir in the downstream end of the sandtrap. The master student Steinkjer (2018) presents the particle deposition pattern and particle size distribution curves for the annotated positions in Figure 5 and Figure 6. These data were collected during a field trip the 2018-08-20. A subsequent field trip the 2020-06-15 confirmed that the same deposition pattern and particle sizes were consistent. In general, sand with d_{50} less than 1 mm deposits close to the downstream weir (position 1 and 2), while gravel and coarser sand with d_{50} around 10 mm deposits further upstream in the sandtrap. The invert between the two positions was almost clean.

Figure 4: Deposited sand upstream the weir in the downstream end of the sandtrap

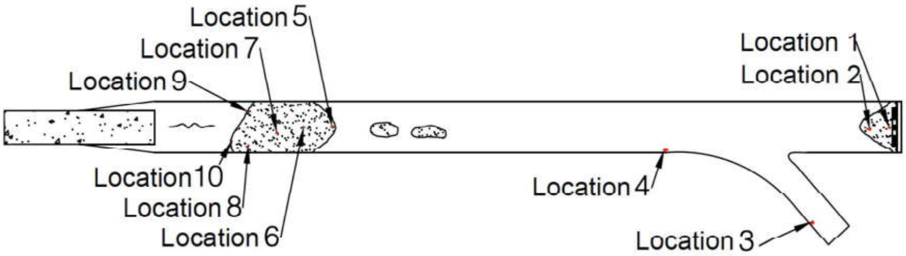

Figure 5: Plan view illustration of the sediment deposition pattern and samples taken in sandtrap no. III (Steinkjer, 2018)

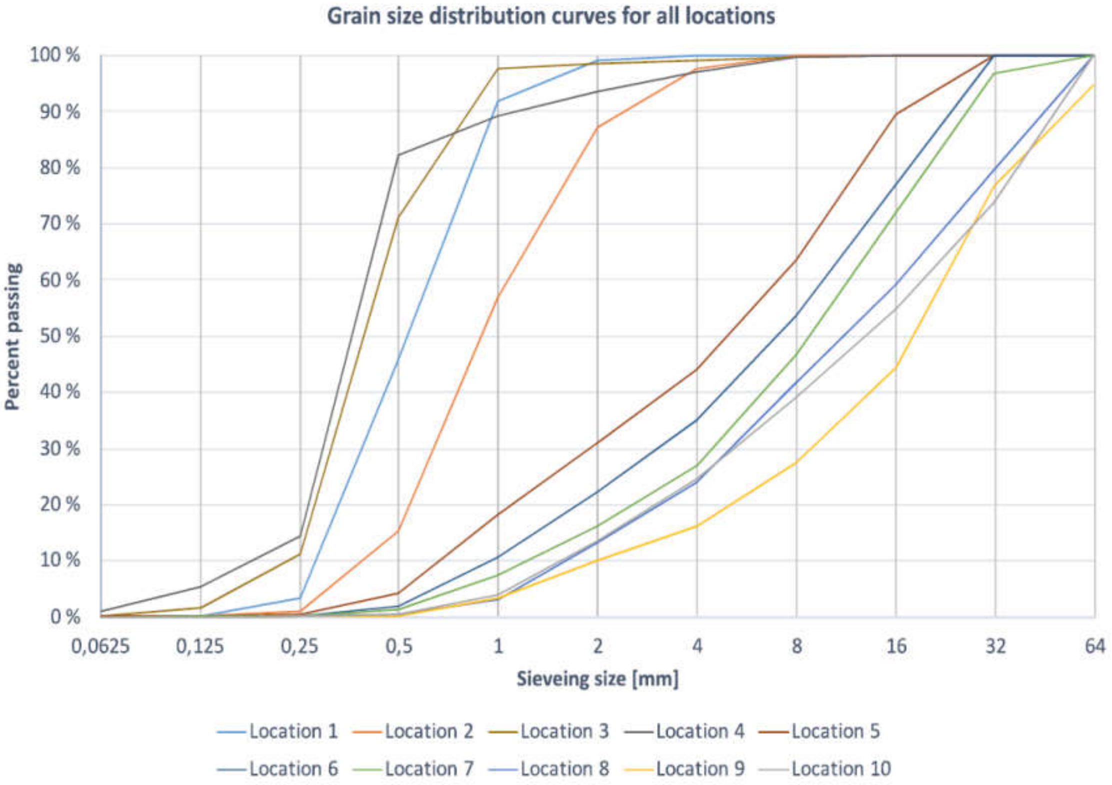

Figure 6: Grain size distributions of the collected samples

During the field trip the 2020-08-18, as sand trap camera was installed in the downstream end, close to the thrash rack, as shown in Figure 7. The purpose was to study the deposition pattern of sand during operation, in addition to monitoring clogging of the trash rack. The camera did not function as intended as the amount of fine silt and humus in the water made the visibility limited. However, the camera was able to film the filling sequence of the sandtrap, disproving a previous theory that the filling process was flushing particles into the turbines. An attempt to also improve the visibility by moving the light source away from the camera position is planned. The pictures below show the sandtrap camera and the sand deposit upstream the weir before and after cleaning. It is noted that sand was also seen on the inside of the trash rack, indicating that the sand is transported over the weir. Figure 8 presents a picture taken during cleaning of the sandtrap.

Figure 7: The sandtrap camera mounted close to the trash rack

Figure 8: Cleaning of the sandtrap

4 Numerical simulations of preliminary concepts (A2)

4.1. Existing situation

This section presents results from 3D CFD simulation of the existing situation in the case-study Tonstad sandtrap. The purpose is to map the existing situation as a benchmark for potential improvements. There are several challenges for modelling of the existing situation such as (1) unknown upstream effects from an upstream bifurcation, (2) effect of the geometry and flow into the surge tank, (3) the complex gate and inlet geometry, (4) unlined and variable rock surfaces.

Figure 9, taken from Appendix 3 presents a transient 3D CFD simulation of the shear stress acting on the invert of the existing sandtrap. The model is extended to cover parts of the headrace tunnel including a bifurcation that influences the inflow condition. Blue color indicates low shear stress down to 0 Nm^{-2} and red color indicates higher shear stress up to 10 Nm^{-2}. Higher shear stress indicated a higher capacity to transport particles. According to USGS (2008) gravel is transported at about 10 Nm^{-2} and sand is transported at about 0.3 Nm^{-2}.

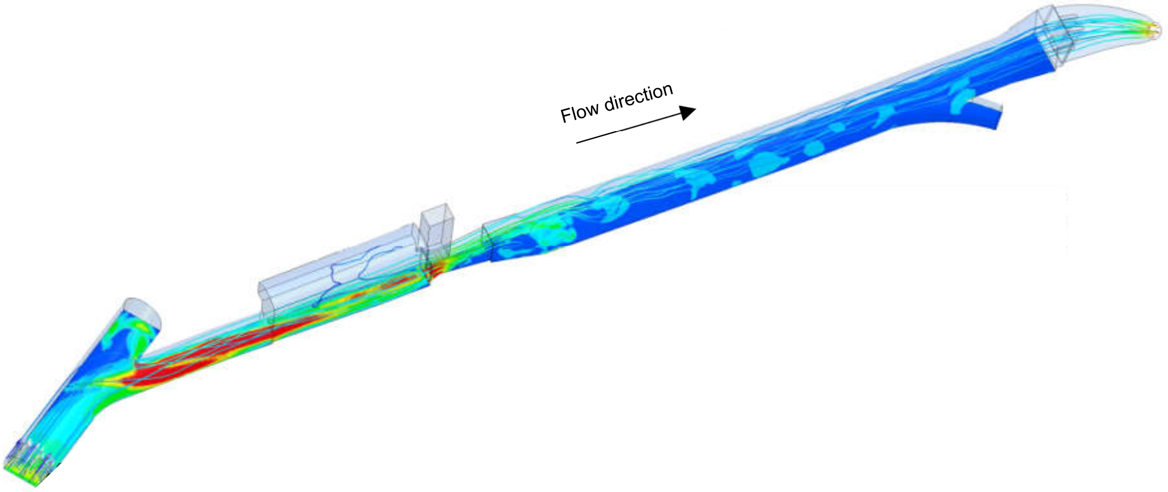

Figure 9: Transient 3D CFD simulations of the shear stress acting on the sandtrap invert

Several 3D CFD models were used to map the existing situation in the case-study Tonstad sandtrap. However, as expected the results were variable depending on the geometry, resolution, and numerical methods applied. Previous research has also been conducted on 3D CFD simulations of this sandtrap (Brevik 2013, Bråtveit and Olsen 2015, Almeland et al. 2019) describing the modelling, calibration with field measurements and challenges. Based on these experiences, the results from the CFD simulations are regarded as indicative and are subjected to qualitative interpretation. For testing of different concepts for upgrading the existing sandtrap, all the CFD users have made simulations of both the existing situation and the results of the tested concepts so that the concepts can be qualitatively evaluated.

4.2. Closed sandtrap with ribs

This section presents the concepts tested with numerical simulations and results generated for reconstruction to closed sandtrap with ribs. The master student Rakel Næss (2019) used numerical simulations to study the trap efficiency with and without ribs. Only one configuration of the ribs has been tested, namely 1 m wide and 1 m spacing between the ribs, based on the recommendations from Eggen (1973) and VR (1984).

The ribs are installed at the same height as the weir in the downstream end of the sandtrap, 1.5 m above the invert, and are installed in a horizontal line across the sandtrap length. As the invert has a downhill slope toward the downstream end, the distance between the ribs and the invert thus becomes smaller toward the upstream end, until the rib section is stopped when they reach the invert. Figure 10 presents the resulting geometry.

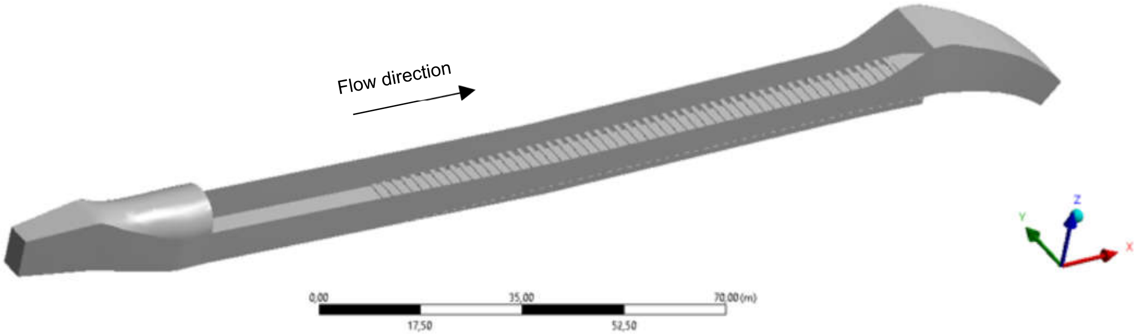

Figure 10: Geometry of the sandtrap for 3D CFD simulations (Næss, 2019)

The results showed that the trap efficiency for Tonstad sandtrap could be improved from 88 to 93% by installing ribs in the full length of the sandtrap. These results are not regarded as final but were convincing to proceed with the closed sandtrap to physical model testing.

4.3. Flow calming structures

This section presents the concepts tested with numerical simulations and the results generated for installation of flow calming structures in existing sandtraps. For many sandtraps, the inflow section might have an abrupt change in the geometry causing turbulence into the sandtrap. For the Tonstad sandtrap this is especially critical as there is a gate in the upstream end with a significant contraction of the cross section. The water thus enters the sandtrap as a jet with high velocity. A flow calming structure may therefore have a positive effect on dampening this jet and reaching uniform flow faster. Figure 11 presents some of the investigated concepts.

Appendix 3 presents numerical simulations of a flow calming structure for the Tonstad sandtrap. The flow calming device was constructed as 52 pipes with 1 m diameter and 8 m length. Comparison of 3D CFD simulations with and without this flow calmer indicated that it had a positive effect on the trap efficiency. The simulations showed that particles fell to the invert further upstream with the flow calmer. This was convincing to proceed with testing with physical modelling.

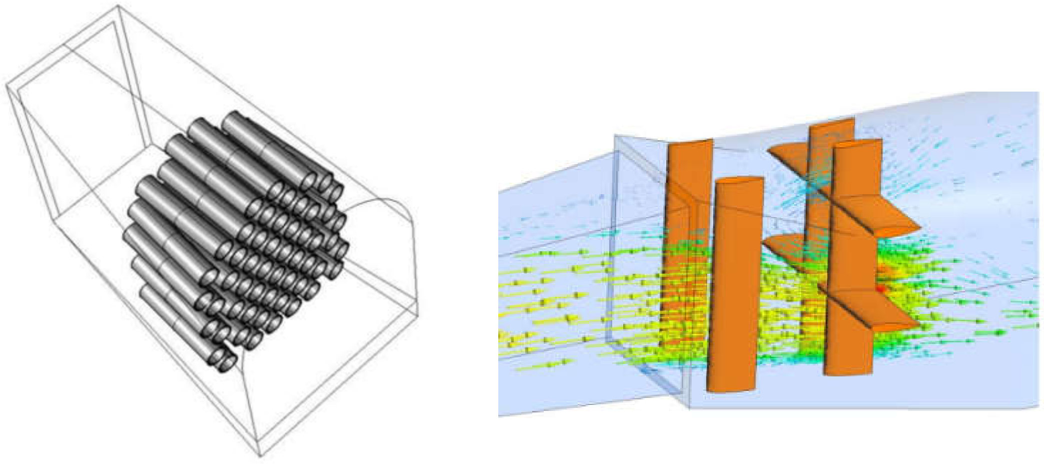

Figure 11: Some of the tested flow calming structure concepts

Appendix 4 presents 3D CFD simulations of several different flow calming devices. The final suggestion is constructed as a passable steel grids separated in two main components that can be passed through by personnel and machines after dewatering and is presented in Figure 29. The effect of the flow calmer was indirectly tested by investigating how efficient the inlet jet was calmed and the flow becoming uniform. The results showed that without the flow calmer, water with velocity higher than 1 m/s is reaching approximately 100 m into the sandtrap. By installing the flow calmer, this is reduced to almost half. These results indicate that the flow calmer would have a positive effect on the trap efficiency. This was convincing to proceed with testing with physical modelling.

4.4. Geometrical improvements

Theoretically, the particle sedimentation process shall be more efficient when the flow is calm and stationary. Thus, geometrical features that disturb the flow should be avoided. Construction of sandtraps in Norway is predominantly with drill and blast tunnels where the rock surface is left unlined. This results in a rough surface and a variable cross section size. Also, the transitions from unlined rock to concrete walls near the downstream pressure shaft and/or upstream gate will also represent potential disturbance to the flow.

For the case-study sandtrap at Tonstad hydropower plant, all these geometrical features are present. There is a transition from a concrete casing around the gate at the upstream end, there is unlined rock surface throughout the sandtrap, and there is a transition to a concrete lined section at the trash rack and pressure shaft in the downstream end. In addition, there is a bifurcation of the tunnel to a gated plug serving as the access point for inspection and emptying of the deposited material. All these elements represent disturbances to the flow.

Figure 12 presents numerical simulations of the inlet section of the sandtrap. Here, a flow separation was found to occur at the transition from concrete to unlined rock. This flow separation results in a significant increase of the turbulent kinetic energy. This situation can be improved by smoothening the transition to avoid the flow separation. Note that this simulation does not include the unlined rough surface and the access tunnel.

Such geometrical improvements are assumed to have a positive impact on the trap efficiency. However, the accumulated impact is not expected to be highly significant compared with the other measures and has hence not been prioritized for investigation in the physical models.

Plan view

Sectional view

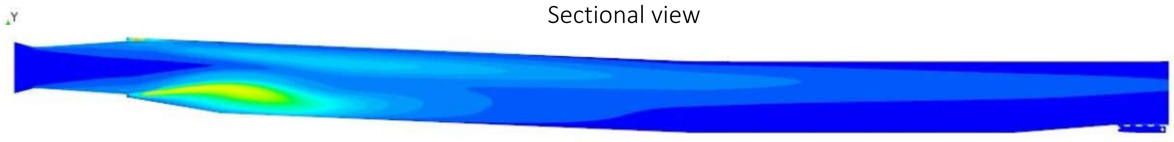

Figure 12: Turbulent kinetic energy in 3D CFD simulations (blue is low and yellow is high).

4.5. Baffles

This section presents a concept that was tested with numerical simulations and the results generated for installation of baffles in existing sandtraps. Appendix 3 presents 3D CFD simulations of installation of baffles for the Tonstad sandtrap, as seen in Figure 13. The hypothesis was that the baffles would increase the roughness of the invert to improve settling, and guide the bedload into a collection trench in the middle of the cross section, from which the trapped material would be sluiced out with an automatic sluicing system e.g. SediSluicer. The baffles were constructed as 0.8 m high concrete blocks anchored to the invert with rock bolts. This concept included a lowering of the original invert. Comparison of 3D CFD simulations with and without the baffles indicated that it had a positive effect on the trap efficiency. The simulations showed that particles fell to the invert further upstream with the baffles. This was convincing to proceed with testing with physical modelling.

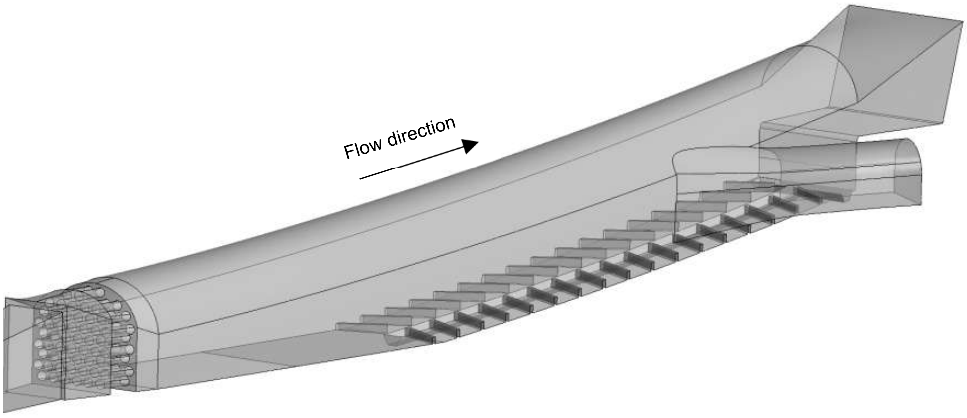

Figure 13: Geometry of the sandtrap with flow calming structure, baffles and trench

4.6. Heightening of the downstream weir

Heightening of the downstream weir was assumed to have three potential positive effects; (1) allow a larger volume of particles to be stored before they reach the top of the crest, (2) make the distance from the invert to the top of the crest higher thus making it more difficult for sand to pass, and (3) protect against free surface flow in the sandtrap. The first two could be positive effects for all sandtraps, while the third is only relevant for pressurized sandtraps constructed in conjunction with an inlet gate or a surge tank. In the latter case, gate operation, mass oscillations, or high headloss may result in the water level dropping down to the level of the sandtrap, causing free surface flow. This situation is known to have occurred in two hydropower plants in Norway, namely the 270 MW Skagen and 960 MW Tonstad power plant. As these sandtraps are designed for pressurized operation, the result has been that the water velocity has increased significantly and scoured the material inside down into the turbines causing significant damage. Owing to the risk of reoccurrence of such incidents, operational restrictions are enforced at both Skagen and Tonstad.

For pressurized sandtraps constructed with a gate at the upstream end, the filling process is of especial importance. The filling of water into an empty sandtrap must be done carefully to avoid fast flowing water from scouring the remaining material on the invert. In the example of the 960 MW Tonstad hydropower plant, the gate dimensions are 4 x 7 m with about 50 m water pressure on the upstream side in closed position. Should this gate be opening fast, it would result in massive scouring of the invert. Hence, the opening procedure at Tonstad is open the gate maximum 50 mm for filling. This process was filmed with a video camera installed in the downstream end of the sandtrap as a part of the FlekS project, proving that the filling process is safe and does not result in scouring. Numerical simulations of a situation where the gate is opened to fast has been carried out by the master student Oddmund Breivik (2013). This may result in a hydraulic jump in the downstream end of the sandtrap that will have a severe particle transport capacity.

Heightening of the downstream weir will limit how low the water level can fall and thus the maximum velocity in the sandtrap should such situations encounter. Heightening of the downstream weir was not tested with numerical simulation. However, it was regarded as a promising concept and was hence put forward for testing with physical modelling.

4.7. Upgrading of surge tanks connected to sandtraps (the “Semi ACST")

This section presents numerical simulations of a concept for upgrading of surge tanks that are constructed in conjunction with sandtraps. The purpose is to avoid free surface flow in the sandtrap during downsurge of the mass oscillations, and obtaining the same results as heightening of the weir. However, the concept developed in this project also provides a higher capacity for the upsurge of mass oscillations.

The semi air cushion surge tank (semi ACST) is constructed as a bifurcation tunnel connected to the sandtrap downstream of the inlet gate (if any). This gives the opportunity to conduct the construction works without dewatering the main tunnel. The tunnel must be constructed with an upward slope until the invert is at an elevation higher than the crown of the sandtrap. This will create an additional lower chamber for the surge tank. The additional component of the semi ACST is an aeration shaft to a point above the upper surge chamber. By tuning the capacity of the aeration shaft, an air cushion effect can be utilized to delay the filling and emptying of the semi ACST to also provide increased capacity for upsurge.

This concept may allow upgrading of the installed capacity in existing hydropower plants, where the capacity of the surge tank is the main limitation. Figure 14 and Figure 15 below present how the semi ACST can be constructed for the Tonstad hydropower plant. Results presented in Appendix 4 show that the proposed dimensions may allow for a 20% increase of the installed capacity in Tonstad hydropower plant.

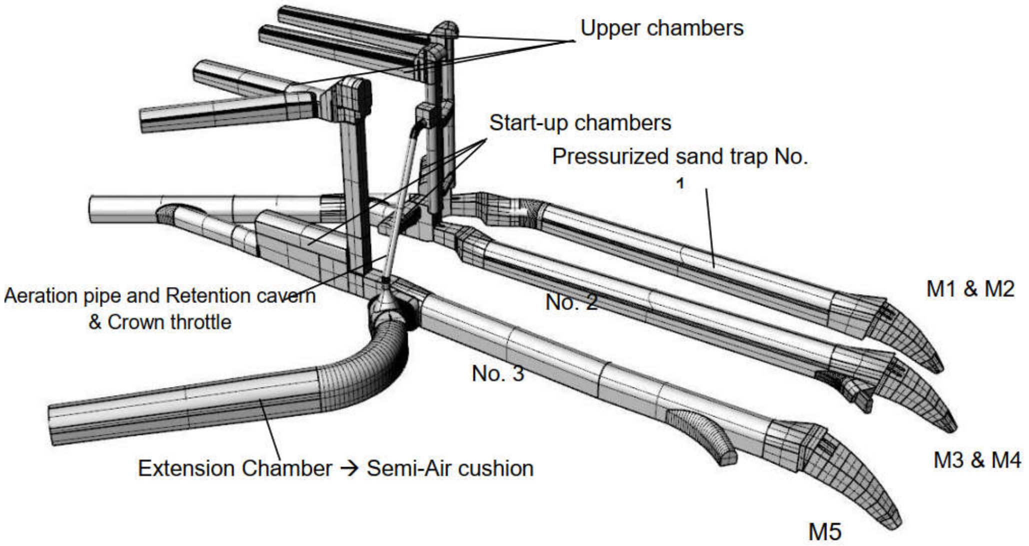

Figure 14: Three-dimensional (3D) model of the proposed semi ACST for Tonstad hydropower plant.

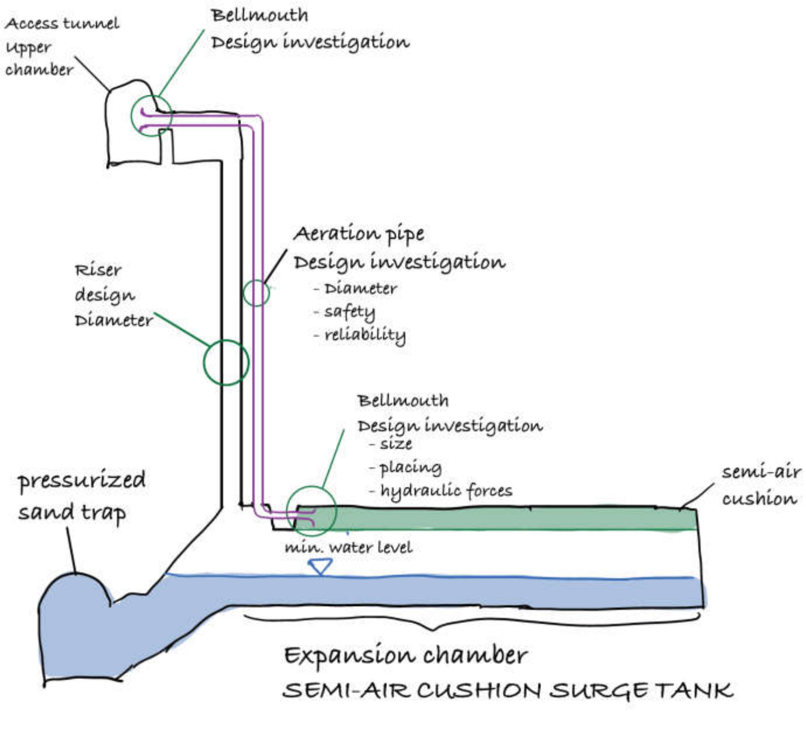

Figure 15: Schematic drawing of the proposed semi ACST

5 Physical modelling of the most promising concepts (A3)

5.1. Existing situation

This section presents the physical modelling results for the existing situation for the case-study sandtrap in the 960 MW Tonstad hydropower plant. The results from the NTNU-model and the TU Graz model are significantly different.

The model at NTNU is constructed in scale 1:20 and the flow and particles are scaled according to the Euler scaling law. For particle Reynolds numbers higher than 400 the dimensionless shear stress is constant and yields that the scaling of particles is consistent with the scaling of water. The particle size distribution was between 10 mm and 0 mm with a d_{50} of 3 mm in prototype scale. The particles were inserted in the top of the cross section at the inlet, through a pipe upstream the gate. A photo of the model is presented in Figure 16.

The trap efficiency of the NTNU model of the existing sandtrap was found to be 87%. The sand deposited very evenly in a thin layer across the sandtrap invert, as seen in the photo in Figure 17 taken from the middle section of the sandtrap. Some minor ripples were observed. Tests were done with both steady state flow, and unsteady state simulating five start-stops of the turbine. There was no significant difference in the results.

Figure 16: Side view of the physical model at NTNU (flow direction from left to right)

Figure 17: Sand deposition after the test of the existing situation

The model at TU Graz is constructed in scale 1:37 and the flow velocity and particles are scaled 1:1 compared with the prototype. The model setup is presented in Figure 18. The selected particle size was between 1.0 and 0.3 mm representing the particle size found deposited upstream the weir in the prototype. The particles were inserted by manually pouring in a defined volume of sand upstream the gate.

The trap efficiency of the TU Graz model of the existing sandtrap was found to be 0%. The sand was transported as bedload throughout the entire sandtrap and continued down into the pressure shaft. The sand accumulated for a short time upstream the weir but was over time completely flushed through. This was the case for flow both equal to the design flow of 80 m^3/s but also the minimum operational flow of 55 m^3/s. The only difference was the time until all the particles were transported over the weir. Vertices appearing upstream the weir was seen to have a large influence on the final particle transport over the weir. Figure 19 present a snapshot from a test of the existing situation.

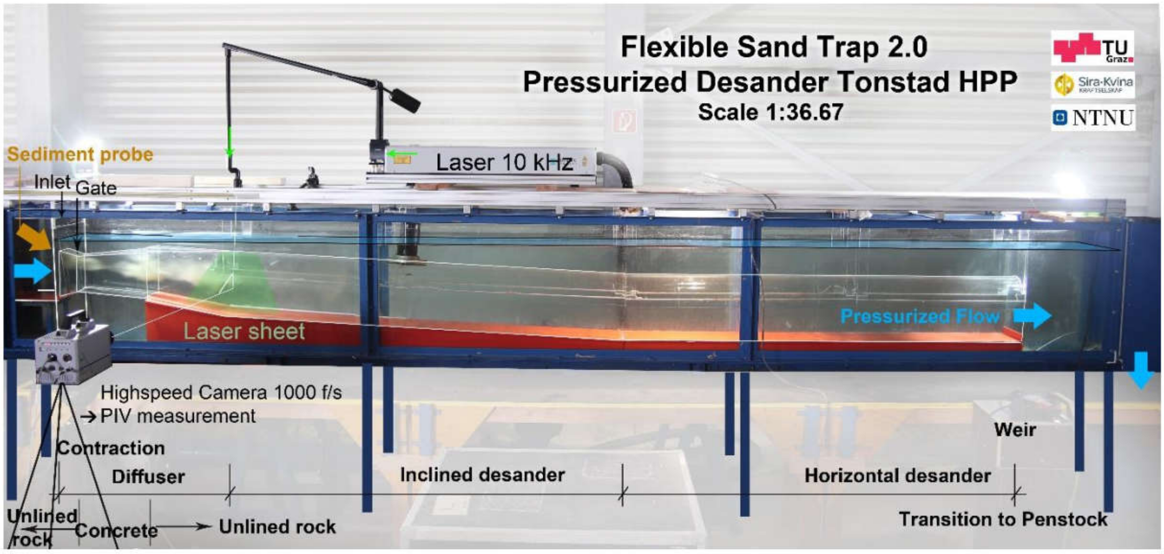

Figure 18: Overview of the physical model at TU Graz

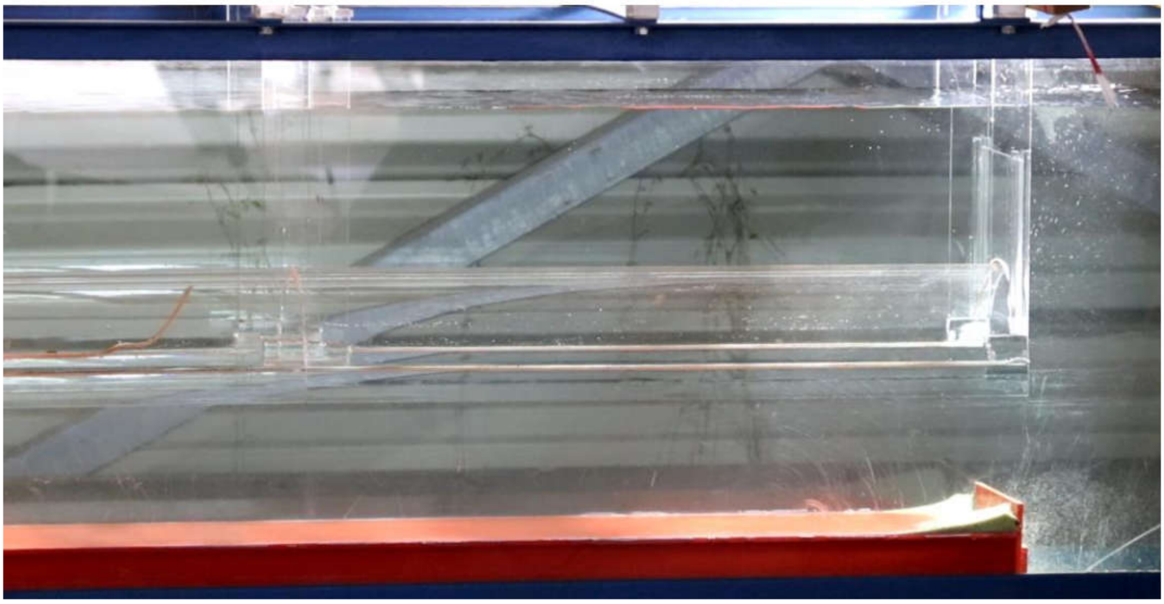

Figure 19: Sand transport for the tests of the existing situation

The results from the TU Graz model seem most similar to the field measurements from the prototype presented earlier in this report. The field measurements show that sand with the same size as in the TU Graz model deposits close to the weir and was also found on the inside of the trash rack downstream the weir. If the results from the TU Graz model is correct, it may indicate that the sand found upstream the weir during each dewatering and emptying is in fact sand that will be transported through the turbine over time.

5.2. Closed sandtrap with ribs

This section presents the concepts tested with physical scale modelling and the results generated for reconstruction to closed sandtrap with ribs. Two different concepts have been tested (1) ribs installed in the full length of the sandtrap and (2) ribs installed in parts of the sandtrap.

Appendix 1 presents results from physical modelling at NTNU of ribs installed in the full length of the sandtrap. Figure 20 present a schematic drawing of the model setup. This setup is similar to the one master student Rakel Næss (2019) used for numerical simulations. The ribs are 1 m wide and have 1 m spacing between the ribs. The ribs are installed at the same height as the weir in the downstream end of the sandtrap, 1.5 m above the invert, and in contrast to the design tested by Næss (2019) the ribs are now continued all the way to the concrete diffusor at the inlet. The ribs are combined with a flow calming structure and a heightening of the concrete ramp so that it meets the first rib 1.5 m above the original invert. The results showed that the trap efficiency for Tonstad sandtrap was not significantly improved even by installing ribs in the full length of the sandtrap. The trap efficiency remained at about 87% both with and without ribs.

The results from the NTNU model were surprising, as a larger improvement of the trap efficiency was expected from this combination of ribs, flow calming structure and improving the geometry at the inlet. However, as the trap efficiency of the existing situation was also found to be relatively high, the potential for improvement was limited compared with the TU Graz model.

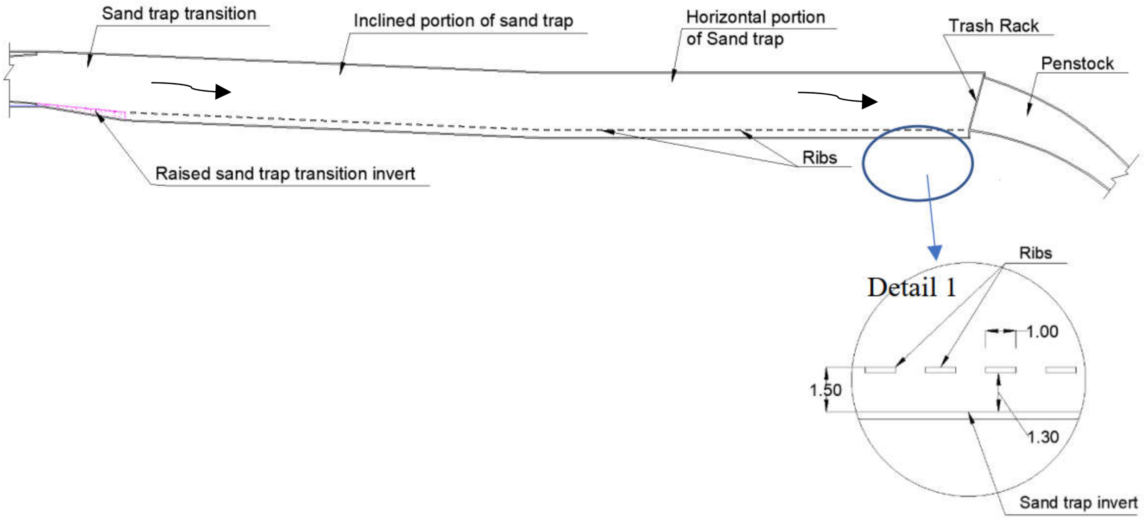

Figure 20: Schematic drawing of the model setup for tests of ribs at NTNU

Appendix 4 presents results from physical modelling at TU Graz, and Figs 21-24 presents pictures from the report. Here the ribs are only installed in a short section at the downstream end of the sandtrap, as seen on the pictures below. In this setup, five ribs are combined with a ramp with 8% inclination. It was tested if the first and last rib should be connected with the ramp and weir without spacing, leaving four open spaces where sand can fall down into the volume below the ribs, as seen in the picture below. This setup was found more efficient than leaving and open space immediately after the ramp and immediately before the weir. The modelled ribs are equivalent to 1 m wide, 1 m spacing and located with the top at the same height as the downstream weir (1.5 m above the invert) similar as to the NTNU model.

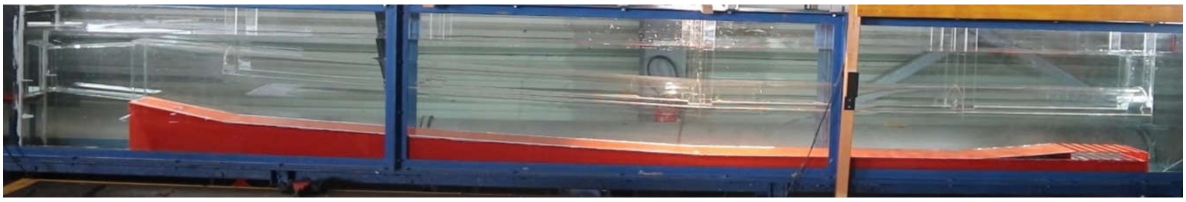

Figure 21: Model setup for tests of ribs at TU Graz (flow direction from left to right)

Figure 22: Snapshot of the sand transport from a test with ribs without a ramp (0% trap efficiency)

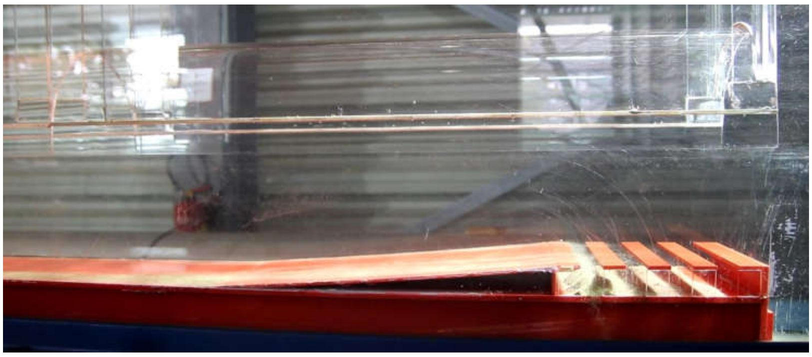

Figure 23: Snapshot of the sand transport from a test with ribs and a ramp (90% trap efficiency)

Figure 24: Comparison of the injected and trapped sand from a test with ribs and a ramp

With this setup the physical model tests at TU Graz obtained a trap efficiency of almost 90%. As the trap efficiency of the existing sandtrap was found to be 0%, the improvement was significant. The result was found to be sensitive to the concentration of particles injected in the model. A higher concentration of sand passing the sandtrap, resulted in reduced trap efficiency. Injection of 500 ml particle in "one-shot" (high concentration) compared with over 25 s (lower concentration) was found to reduce the trap efficiency with about 15%. Tests were also conducted without the ramp upstream the rib section. The results from these tests were 0% trap efficiency, proving the need to install the ramp.

In addition to the test of the overall influence of ribs on the trap efficiency, a detailed investigation of the flow field around and in between the ribs was carried out at NTNU, as described in Appendix 2. The investigation was conducted with particle image velocimetry (PIV) around two of the ribs in the downstream end of the sandtrap. The rib setup was the same as for the trap efficiency test with 1 m wide and 1 m spacing between ribs. The model was adapted by removing the access tunnel, and providing a flow calming structure at the inlet, to remove site-specific effects of the Tonstad layout and make the results more generally valid. The purpose of the investigation was to confirm that the ribs separate the flow in high velocities above and lower velocities below the ribs and see how the behavior is for different flow velocities. Details measurements and analysis where conducted, and further research is planned to assess the optimum design of the ribs.

Figure 25 and Figure 26 presents the camera setup and graphs of the measured flow vorticity and velocity around the ribs. The results showed that the ribs separate the flow field into higher velocities above and lower velocities below the ribs. The ratio was 2.5:1 for 20 l/s and 5:1 for 140 l/s, and 3:1 for 45 l/s which is equivalent to the design flow of 80 m^3/s in sandtrap no. III in Tonstad power plant.

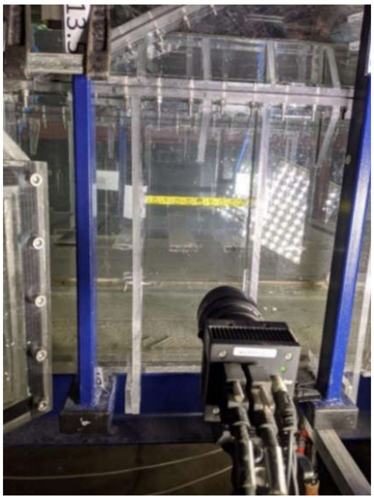

Figure 25: The camera setup for the PIV measurements of the flow field around ribs

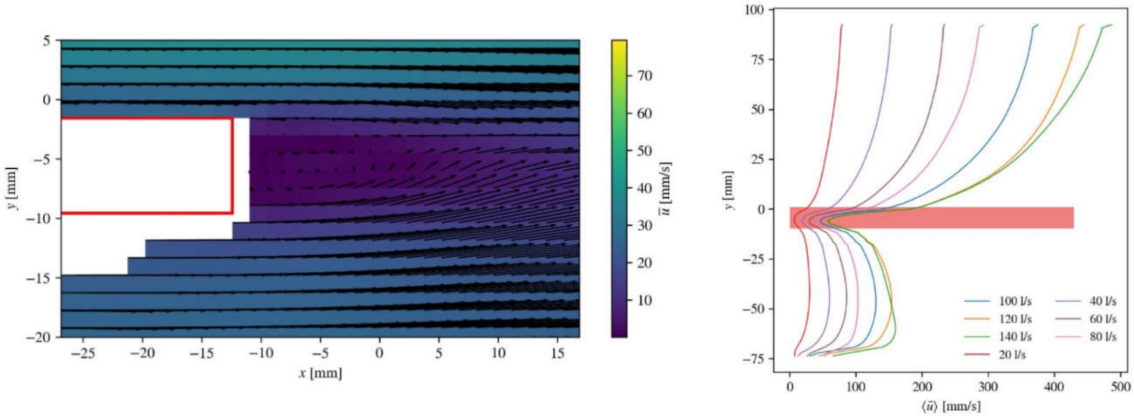

Figure 26: Results from the PIV measurements illustrating the flow field around the ribs (flow from left to right)

5.3. Flow calming structures

This section presents the concepts tested with physical scale modelling and the results generated for installation of flow calming structures in existing sandtraps. Three different model tests were done on flow calming structures. The master student Jana Daxnerová (2019) studied three different type of flow calming structures in a hydraulic free surface flume. One type of flow calming structure was tested at NTNU described in Appendix 1, and one type was tested at TU Graz described in Appendix 4.

The master student Jana Daxnerová (2019) conducted model test of three flow calming structure in a hydraulic experimental flume with free surface flow. The three alternatives are shown in Figure 27. The flume was 0.6 m wide and structures replicating the inlet and outlet of the prototype Tonstad sandtraps was installed with 17.5 m distance. The resulting model scale is 1:17.

The trap efficiency of the model without the flow calmer was about 95%. All the flow calmers improved the trap efficiency to over 99%. In addition to the trap efficiency, the effect on the headloss for each of the alternatives was measured. The resulting headloss for each of the flow calmers was found to be about 5, 20 and 2 mm respectively. The flow calmer no. 3 was hence recommended for further testing. For further details, the reader is referred to the full master thesis available at the NTNU open archives.

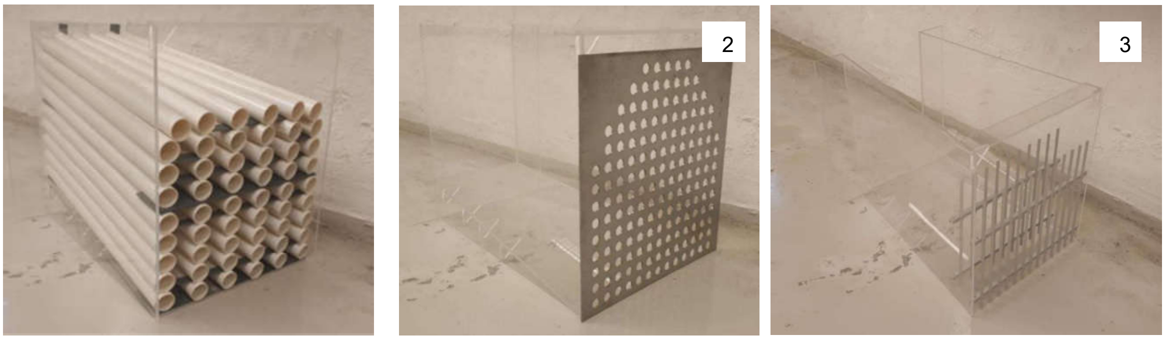

Figure 27: The three different flow calming structures tested by Daxnerová (2019)

The flow calmer recommended by Daxnerová was also tested in the 1:20 model at NTNU, as described in appendix 1. The flow calmer was placed in the downstream end of the diffusor downstream the gate. The two parts of the flow calmer was placed with 7 cm spacing. The results showed that the flow calmer increased the trap efficiency from 89 to 94% resulting in a 5% improvement. The headloss was measured to increase from 40 mm to 130 mm in prototype scale, indicating that the flow calmer increases the total headloss with about 90 mm in prototype scale. Figure 28 presents the flow calming structure installed in the 1:20 physical model.

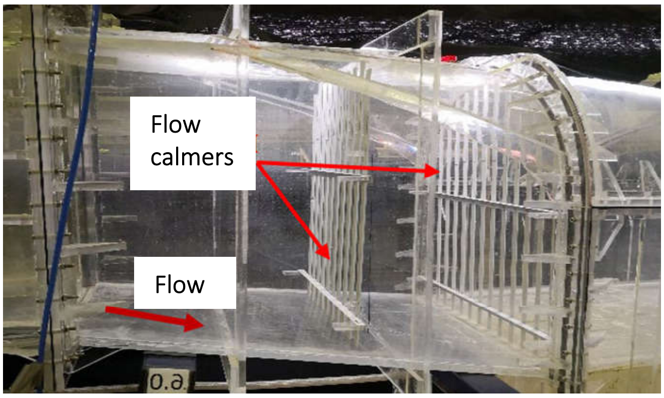

Figure 28: The installed flow calming structure in the physical model at NTNU

Another type of flow calmer was tested in the model at TU Graz. The design criterion was that the flow calmer should be passable with personnel and machines when dewatered, to allow inspections and work without dismantling the flow calmer. Different variant of the design was first tested with CFD as described earlier, and one final version was put forward for physical model testing. The final design is seen in Figure 29. For testing of the flow calmers, the model setup with ribs was used to be able to assess the impact on the trap efficiency (without ribs the trap efficiency was 0% for all cases).

The results from the physical model at TU Graz varied depending on the discharge, but on average the flow calmers decreased the trap efficiency with 10% compared to the setup without ribs. For the design flow, the trap efficiency was reduced from 75% to 65%. Note that these results are with “one-shot” particle injection, which is more adverse than the particle injection for the test setup with ribs.

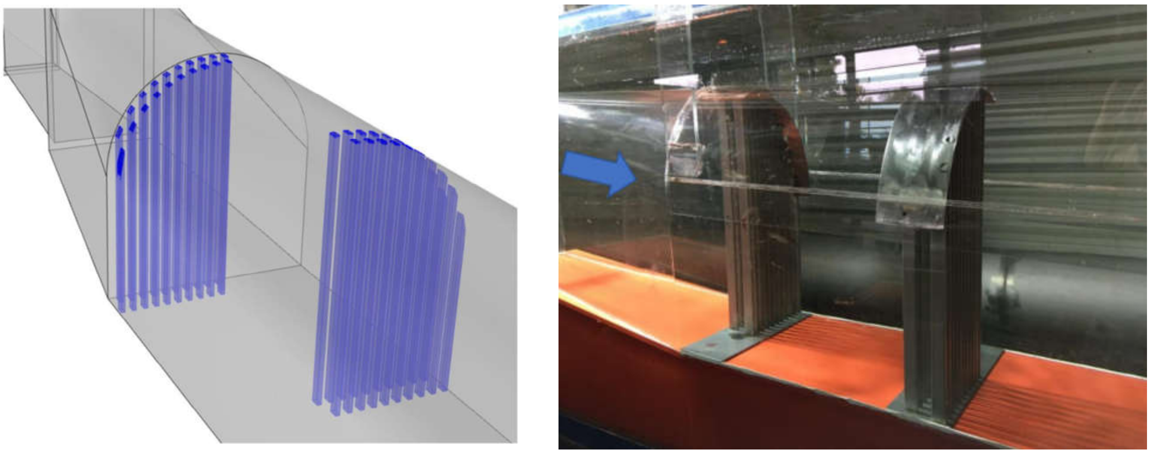

Figure 29: Three dimensional (3D) model and physical model of the flow calming structure tested at TU Graz

5.4. Heightening of the downstream weir

This section presents the concepts tested with physical scale modelling and the results generated for heightening of the weir in the downstream end of existing pressurized sandtraps. Heightening the weir was assumed to have three potential positive effects; (1) allow a larger volume of particles to be stored before they reach the top of the crest, (2) make the distance from the invert to the top of the crest higher thus making it more difficult for sand to pass, and (3) protect against free surface flow in the sandtrap.

Heightening of the weir was tested in the physical model at NTNU. The model weir was increased by simply placing a plate on the upstream end of the trash rack, effectively blocking 50% of the flow area as seen in Figure 30. Apart from this modification, the model remained similar as for the existing situation in the prototype. The heightening of the weir had a neglectable effect on the trap efficiency. The trap efficiency was measured to 87% both before and after the heightening of the weir. The effect on the headloss was also neglectable.

Heightening of the weir was also tested in the physical model at TU Graz. Three different heights were tested, and apart from this modification the model was similar as for the existing situation in the prototype. For all the three different heights, the trap efficiency remained at 0%. The main difference was the time it took for the sand to be transported over the weir. In prototype scale the time was 2 h, 5 h and 6 h for the 1.3 m, 2.6 m and 3.9 m high weirs respectively. Picture from tests of the three weir heights are shown below.

The pictures in Figure 31 show snapshots of the sand transport over the weir for the 1.3 m, 2.6 m and 3.9 m high weirs respectively. The photos are taken at different time relative to the sand injection and the accumulated volume upstream the weir cannot be directly compared. However, the pictures show that there is sand transport over the weir for all cases.

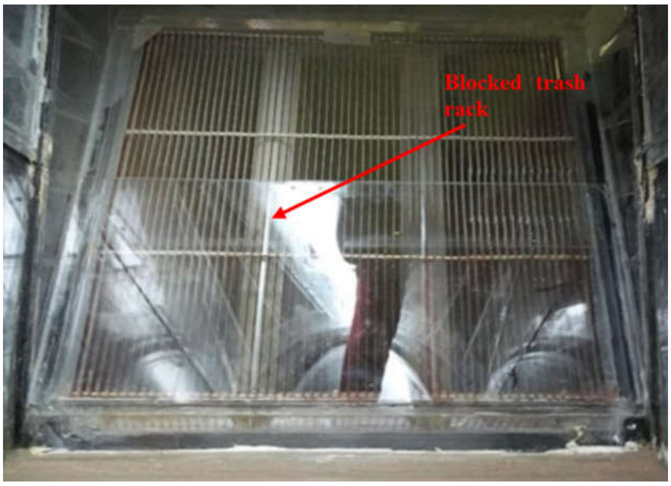

Figure 30: The physical model setup for testing heightening of the weir at NTNU

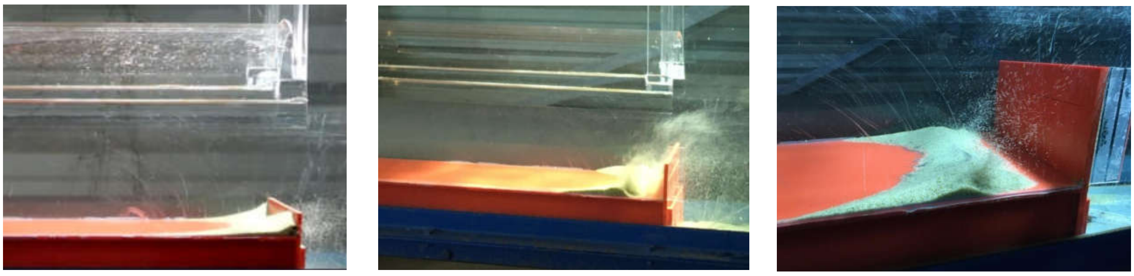

Figure 31: Snapshots from tests at TU Graz with original weir height (left), double height (middle) and triple height (right)

6 Main findings and discussion

This chapter presents the main findings and a discussion of the results. The FlekS research project has resulted in several interesting findings related to knowledge about silt, sand and gravel problems in the hydropower industry, concepts for upgrading of existing pressurized sandtraps, sandtrap research methodology and the potential for upgrading of existing hydropower plants.

6.1. Particle problems in high-head hydropower plants

The literature review and discussions with the hydropower industry revealed that problems related to transport of sand and gravel are significant. Hydropower plants comprising over 8000 MW equaling over 25% of the total installed capacity in Norway has experience challenges related to silt, sand and gravel transport through the turbines. Many of these power plants have pressurized sandtraps that are not functioning satisfactory. These results demonstrate a large potential for new concepts for upgrading of existing sandtraps in hydropower plants.

6.2. Most promising concepts

Reconstruction from open sandtraps to closed sandtraps is regarded as the most promising concept for upgrading of existing sandtraps in hydropower plants. This concept is tested in both 3D CFD simulations and physical model tests and showing a promising improvement of the trap efficiency. In the physical model test at TU Graz, the trap efficiency was improved from 0% to 90% for particle sizes between 0.3 mm and 1 mm in prototype scale, which is the same size as found upstream the weir in the prototype.

The most time-efficient and cost-efficient concept is to install a short section of ribs in the downstream end of the sandtrap. A ramp with inclination 8% is installed in the upstream end of the rib section and the rib section ends at the weir in the downstream end. The short rib section must be complemented with a flushing system to avoid sand from completely filling the volume below the ribs within short time. The concept with a shorter section of ribs and a ramp is planned to be installed and tested at the 960 MW Tonstad hydropower in 2023 simultaneous with a revision of the turbine and upgrading of the control system. For practical installation it is considered to construct the ramp and ribs in aluminum to allow easy installation and dismantling. The rib dimensions may be increased to 1.2 m wide and 1.2 m spacing to conform to the standard freight dimensions. The SediSluicer (https://sedicon.no) is considered to be installed as flushing system. It is foreseen to distinguish between gravel sluicing at the upstream end of the sandtrap and sand sluicing below the rib section.

The results for the flow calming structure in the upstream end of the sandtrap was inconsistent. Some of the methods show that such structures have a positive effect on the trap efficiency, while some show a negative effect. These results are inconclusive and further investigation is necessary before this concept can be recommended for upgrading of existing sandtraps.

Heightening of the downstream weir did not have any effect on the trap efficiency. These results were consistent from both the physical model at NTNU and TU Graz. Heightening of the downstream weir may however have a positive effect on reducing the risk of free surface flow with high velocities through the sandtrap. For specific power plants where the pressurized sandtrap may risk free surface flow conditions, this solution may be beneficial.

6.3. Sandtrap research methodology

Two different scaling methods for physical modelling have been applied, and the two methods gave significantly different results. The physical model at NTNU gave almost 90% trap efficiency for the current situation, while the physical model at TU Graz gave 0% trap efficiency. There were several differences in the construction method and applied particle sizes, in addition to the different scaling methods. It is therefore not possible to finally conclude on what is the reason for the large difference.

The method applied at NTNU is the historically most applied and has been applied for several hydraulic scale model tests of sandtraps at NTNU in the past. However, the results from the physical model at TU Graz is most similar to the observed particle deposition in the prototype. If the results from the TU Graz model is correct, the sandtrap in Tonstad hydropower plant does not capture any material below 1 mm, and the sand deposits found inside the sandtrap after dewatering is only the accumulated volume that is awaiting the final transport over the weir.

Developing scaling methods has not been an objective in the FlekS-project, and further research is necessary to investigate the accuracy of the two different scaling methods. Tests in the TU Graz model with the equivalent same sand size as applied in the NTNU model are planned to check if the difference in results is still significant. Tests are also planned to be conducted according to the Euler scaling method with lightweight material (natural sand is not possible at scale 1:37 owing to cohesion). Also, field data from the prototype after the planned installation of the ramp and a short section with ribs, will provide more information to validate the physical scale models. Further investigation of the numerical simulations methods is also required. The turbulence models and necessary resolution, in addition to the particle simulation and two-way coupling between water and particles needs further testing to give credibility as a design method for pressurized sandtraps.

6.4. Upgrading of the installed capacity in hydropower plants

For many existing hydropower plants, either the surge tank or the sandtrap present a major limitation to the potential increase of the installed capacity. However, the results from FlekS highlight the potential to find new solutions to overcome these limitations. A new concept for upgrading of surge tanks constructed in conjunction with pressurized sandtraps (the semi ACST) may allow up to 20% increased installed capacity at the case-study Tonstad hydropower plant.

7 Deliverables

The deliverables from the FlekS project are summarized in this chapter. Work on additional scientific publications is currently ongoing. In total, two journal paper, two conference papers, four research reports, one final report, five master thesis, three presentations, three popular-scientific publications were produced.

7.1. Scientific Publications

Richter W. Vereide K. and Zenz G. (2018). "Surge tank layout for highly flexible hydropower." International Journal of Hydropower and Dams 25(3): 42-46.

Richter W., Vereide K. and Zenz G. (2017). "Upgrading of a Norwegian pressurized sand trap combined with an open air surge tank." Geomechanics and Tunnelling 10(5): 620-624.

Havrevoll O. H., Almeland S. K. and Vereide K. (2018). A new self-flushing rock trap concept for pump-storage plants. Particles in Europe conference. Lisbon, Portugal.

Vereide K., Richter W., Lia L., Havrevoll H. and Jakobsen T. (2017). Upgrading of Sand Traps in Existing Hydropower Plants. Hydro 2017 conference, Seville, Spain.

7.2. Master theses

Rakel Næss (2020). “CFD simulations of Open and Closed Sand Trap Design for Tonstad Hydropower Plant.” Master Thesis, NTNU, Trondheim, Norway.

Gasper Mauko (2020). “Water Hammer Simulations for Tonstad HPP upgrade”. Master Thesis, University of Ljubljana, Ljubljana, Slovenia.

Jana Daxnerová (2019). “Hydraulic Scale Modelling of Flow Calming Structures for Hydropower Plants.” Master Thesis, NTNU, Trondheim, Norway.

Sofie Marie Steinkjer (2018). “Hydraulic Scale Modelling of Particles for Pressurized Sand Traps.” Master Thesis, NTNU, Trondheim, Norway.

Lukas Sterner (2018). “3D CFD simulations for Tonstad surge tanks upgrade”. Master Thesis, TU Graz, Graz, Austria.

7.3. Innovations

Ribs&Ramp concept for upgrading of sandtraps in existing hydropower plants. Presented in Appendix 4.

Semi ACST concept for upgrading of surge tanks. Presented in Appendix 4.

Self-flushing rock trap concept for pumped-storage plants. Presented in Havrevoll et al. (2018).

7.4. Reports

Vereide K., Richter W., Havrevoll O. H., Belete K., Shrestha U., Navaratnam U., Mauko G., and Lia L. 2021. Flexible Sandtraps Final Report. HydroCen Report 20. Norwegian Research Centre for Hydropower Technology. (This report)

Belete K., Shrestha U. and Vereide K. 2020. Physical Model Study of Tonstad Sand Trap III. Final report. NTNU report no. B1-2020. Norwegian University of Science and Technology.

Havrevoll O. H., Vereide K., Rüther N. and Lia L. 2021. PIV experiments on ribs in the Tonstad rock trap model. NTNU report no. B1-2021-2. Norwegian University of Science and Technology.

Richter W. and Zenz G. 2020. Flexible Sandtrap (FlekS) 1.0. Final report. Graz University of Technology.

Richter W., Mauko G. and Zenz G. 2020. Flexible Sandtrap (FlekS) 2.0 Project extension. Final report. Graz University of Technology.

7.5. Presentations

2020-11-05, HydroCen scientific group meetings, Presentation, ca. 20 participants.
2018-07-05, Bluesinar, Presentation, ca. 15 participants.
2017-09-12, HydroCen scientific seminar, Presentation, ca. 100 participants.
2017-03-07, Produksjonsteknisk konferanse, Conference, ca. 200 participants.

7.6. Popular-scientific publications

2018-03-13, EnergiTeknikk, Popular scientific magazine, «Forskning skal løse sandfangsproblem», Stein Arne Bakken.
2018-02-03, Møre Nytt, Newspaper, «Rusk i maskineriet». Svein Aam.
2018-09-20, International Water Power and Dam Construction, Popular scientific magazine, “Tunneling research”, Leif Lia and Kaspar Vereide.

7.7. Social media, online and informal communication channels

Vannposten, HydroCen newletters, weekly circulation to HydroCen user partners.
HydroCen webpages.
Sira-Kvina webpages.

8 Conclusions and future work

8.1. Conclusions

In conclusion, it is found possible to upgrade existing sandtraps with limited downtime and costs. The main conclusions from the FlekS research project are presented below.

1. Hydropower plants comprising over 25% of the total installed capacity in Norway have experience challenges related to transport of silt, sand and gravel during operation. Many existing sandtraps do not function satisfactory.
2. The FlekS-project confirms previous research that the closed type of sandtraps is superior compared with the open type of sandtrap for trapping of bed load. The main difference is that the closed type successfully separates the deposited material from the main water flow, preventing further transport as bed load or resuspension.
3. An efficient solution for upgrading of open sandtraps to closed sandtraps has been developed. The solution entails limited construction works in the downstream end of the sandtrap and does not require expanding of the sandtrap volume. This solution has been recommended for the upgrading of the case-study sandtrap at Tonstad power plant. Physical model tests at TU Graz indicate that this solution can increase the trap efficiency from 0% to 90% for particle sizes in the range 0.3 to 1 mm. Physical model tests at NTNU for particle sizes with d_{50} equal to 3 mm do not show any significant different in the trap efficiency for tests with and without ribs (about 87% for both situations).
4. The proposed solution includes the use of a flushing system, which is necessary to enable the minimum reconstruction works inside the sandtrap. Flushing systems are in general found to be a promising measure when upgrading existing sandtraps. Most of the Norwegian sandtraps reviewed in this work do not have a flushing system and require dewatering and manual removal of the deposited material. Flushing systems allow emptying of the deposited material without dewatering the sandtrap and will hence reduce both outage and the stress on the tunnel stability resulting from a dewatering.
5. The results concerning the effect of flow calming structures on the trap efficiency of sandtraps are inconclusive. Some tests show a positive effect, and some show a negative effect. A concept with a passable flow calming structure was developed, allowing personnel and machines to pass the structure without dismantling during dewatering.
6. Heightening of the downstream weir was not found to have any effect on the trap efficiency. However, it may have a positive effect by preventing free surface flow with high velocities in the sandtrap.
7. Geometrical improvements are usually possible in existing sandtraps. Sudden expansions, contractions and abrupt changes in the geometry will cause turbulence and can decrease the trap efficiency of sandtraps.
8. For power plants where the sandtrap is constructed in conjunction with a surge tank, a new innovative solution for combined upgrading of the surge tank is developed. The “semi-air cushion surge tank” is able to increase the capacity of both the upper and lower surge chamber of two-chamber surge tanks with only expanding the volume of the lower chamber. Upgrading of the sandtrap may enable upgrading of the installed capacity in hydropower plants.
9. Physical model tests were not able to confirm any significant difference in trap efficiency for stable operation and transient operation of hydropower plants. However, only one test to investigate this effect was conducted and further research is necessary to conclude.

The results presented above are primarily based on the results from the physical scale models. However, it is experienced that numerical simulations and physical modelling and variations of the two methods gave significantly different results. Three different numerical simulation software were applied by different users and with different setup, and two different scaling methods for the physical modelling were applied. By comparing with the sand deposition in the field measurements, the results from the physical scale model from TU Graz seems to be most representative.

8.2. Future work

Developing scaling methods has not been an objective in the FlekS-project, and further research is necessary to investigate the accuracy of the two different scaling methods. Tests in the TU Graz model with the equivalent same sand size as applied in the NTNU model are planned to check if the difference in results is still significant. Tests are also planned to be conducted according to the Euler scaling method with lightweight material (natural sand is not possible at scale 1:37 owing to cohesion). Also, field data from the future case-study Tonstad sandtrap with installation of the ramp and a short section with ribs, will provide more information to validate the physical scale models. Further investigation of the numerical simulations methods is also required. The turbulence models and necessary resolution, in addition to the particle simulation and two-way coupling between water and particles needs further testing to give credibility as a design method for pressurized sandtraps.

A PhD project in HydroCen will continue parts of the work described in this report. The physical models, the field data, and the 3D geometry for numerical simulations are still available for future research, teaching and master thesis work.

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10 Appendix

Appendix 1: Report from Physical Model Study of Tonstad Sand Trap (NTNU, 82 pp.)

Appendix 2: Report from PIV-measurement of Ribs in the Tonstad Sandtrap Model (NTNU, 17 pp.)

Appendix 3: Report from Flexible Sandtrap (FlekS) 1.0 (TU Graz, 100 pp.)

Appendix 4: Report from Flexible Sandtrap (FlekS) 2.0 Project Extension (TU Graz, 230 pp.)

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ISSN:1504-3312
ISBN: 978-82-93602-21-7

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